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Research Article

Estimates of Aerosol Indirect Effect from Terra MODIS over Republic of Korea

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Moderate resolution imaging spectroradiometer (MODIS) data have been analyzed over four different regions (Yellow sea, Korean inland, East Sea, and South Sea) in Republic of Korea to investigate the seasonal variability of aerosol-cloud properties and aerosol indirect effect during the past decade (2000–2009). Aerosol optical depth (AOD) was found to be consistently high during spring. Cloud ice radius (CIR) also showed higher values during spring, while an enhancement in cloud water radius (CWR) and fine mode fraction (FMF) was observed during summer. AOD and aerosol index (AI) were found to be higher during January to June. However, FMF and CWR showed enhancement during July to December. Aerosol indirect effect (AIE) in each year has been estimated and found to be showing positive and negative indirect effects. The AIE for fixed cloud ice path (CIP) showed positive indirect effect (Twomey effect) over Yellow sea, while the AIE for fixed cloud water path (CWP) showed a major negative indirect effect (anti-Twomey effect) over all regions. During Changma (summer monsoon) period, the AIE for both CIP and CWP showed dominant anti-Twomey effect in middle and low level clouds, indicating the growth of cloud droplet radius with changes in aerosols, enhancing the precipitation.

1. Introduction

Aerosols are known to impact the formation and the life cycle of clouds by acting as cloud condensation nuclei (CCN) or ice nuclei (IN). A wide range of measurements shows that anthropogenic aerosols induce changes in clouds and their optical properties. These changes are popularly known as aerosol indirect effect (AIE) [1–3]. It is important to understand and quantify the microphysical impact of both natural and anthropogenic aerosols on clouds, in order to understand and predict climate change. The main identified AIEs include the cloud albedo effect [4] and cloud life time effect [5]. The "Twomey effect" (positive indirect effect) refers to a decrease in a cloud effective radius with increasing aerosol content for a fixed liquid water path. Contrary to this effect, an increase in the cloud droplet size with the aerosol load, or an "anti-Twomey effect" (negative indirect effect), was also reported in some parts of the world for certain environmental conditions [6]. It has also been reported that the AIE could be an important factor in modulating the response of large scale systems such as monsoons [7–9]. However, studies on AIE and its influence on precipitation are sparse across the world [10–12].

Aerosols in Asian regions are known to be an important factor in modulating different weather phenomenon. Korean peninsula is surrounded by oceanic areas on its three territories. Hence aerosol-cloud properties have been analyzed over three oceanic and the continental region over Republic of Korea. Aerosols in wet environment have a great significance in the development of clouds and precipitation. Especially, heavy rainfalls in East Asian monsoon region are related to Changma/Baiu/Meiyu frontal system [13] and interaction

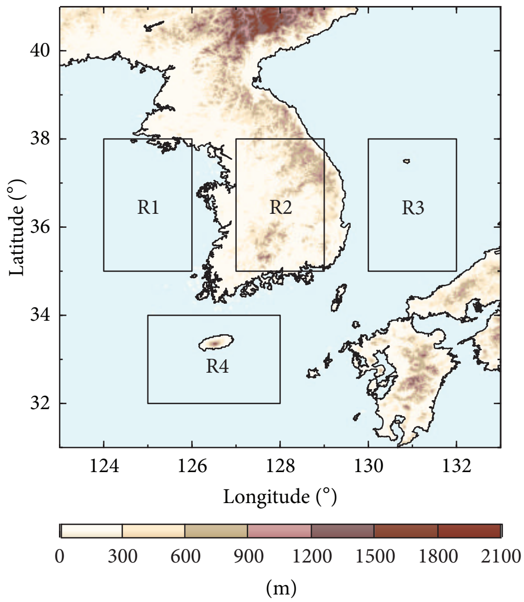

Figure 1: Topographic map of Republic of Korea with selected regions from R1 to R4.

between aerosol and clouds in monsoon is a main important factor [14]. Summer monsoon in Korea is characterized with humid, moist environment [13] and hence aerosol indirect effect could be different as compared with dry period. Clouds in East Asian monsoon region also show different structures and components according to the cloud levels or height [15]. Especially, cloud height and type are shown to be as important as cloud cover in modifying the radiation field of the earth-atmosphere system [16].

In this study, we investigate the seasonal and monthly variability of aerosol-cloud properties and associated indirect effect using Terra moderate resolution imaging spectroradiometer (MODIS) satellite data for four different regions in Korean peninsula. Also the AIE has been exclusively estimated during summer monsoon (Changma) period in different cloud types to find the possible role of AIE in modulating precipitation.

2. Data and Methodology

Oceans exert a strong influence on precipitation development over Korea. The aerosol-cloud properties and their variations were investigated over three oceanic and one continental regions in Korea. The selected regions include Yellow sea (R1, 124°–126°E & 35°–38°N), Korean inland (R2, 127°–129°E & 35°–38°N), East sea (R3, 130°–132°E & 35°–38°N), and South sea (R4, 125°–128°E & 32°–34°N) (Figure 1).

In this study, we used MODIS level 3 daily data sets of aerosol optical depth (AOD), fine mode fraction (FMF), cloud ice radius (CIR), cloud water radius (CWR), cloud ice path (CIP), cloud water path (CWP), Angstrom exponent (ANG), and cloud top pressure (CTP) over Korean peninsula for a period of 10 years (from 2000 to 2009). We also used total ozone mapping spectrometer (TOMS) level 3 daily data sets of aerosol index (AI) over Korean peninsula for 5 years (from 2000 to 2004) and ozone monitoring instrument (OMI) for 5 years (from 2005 to 2009) because of absence of satellite data. The daily data have been averaged to find monthly variations during different seasons namely, spring (March–May), summer (June–August), autumn (September–November), and winter (December–February).

For AIE estimation, each of the selected regions was further subdivided into grids of 1° × 1° and analyses were performed for each grid. The MODIS 1° × 1° derived daily CWP and CIP have been divided into 14 different bins, ranging between 1 and 350 at an interval of 25. The indirect effect for each bin has been calculated using the below expression as explained in [17], that is,

$$\mathrm{AIE} = -\frac{d \ln r_e}{d \ln \tau_\alpha}, \tag{1}$$

where τ_α is aerosol optical depth and r_e is the cloud effective radius (r_e: cloud ice radius for fixed CIP and cloud water radius for fixed CWP). Simple linear regression has been performed between AOD and CIR (for fixed CIP bins) and AOD and CWR (for fixed CWP bins) to estimate the AIE for cloud water and cloud ice radii, respectively.

In addition, back-trajectories were analysed to determine the pathways and origins of aerosol to Korea using hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) from air resources laboratory (ARL). Vertical motion calculation method was isobaric and meteorological data were obtained from national centers for environmental prediction (NCEP), global data assimilation system (GDAS). Back-trajectories were generated for 120 hours back in time from central point in each region.

3. Results and Discussion

3.1. Seasonal Variability of Aerosol Cloud Properties. Regional and monthly variations of aerosol-cloud parameters have been analyzed over the period 2000–2009 and are depicted in Figures 2 and 3. It is found that the aerosol parameters show significant variability, which in turn influences the cloud properties. The AOD, indicating the aerosol loading, [18] is found to have the highest average value (0.45) over R1 compared to other regions (Figure 2(a)). The long-range transport of aerosols from adjacent deserts in Mongolia and China [19–21] could be the main reason for this higher aerosol loading over R1. The AOD values were found to be higher during the period from January to June and were found to have consistently lower values from July to December in all regions. The AOD values were found to be consistently high during spring season (March–May). The average AI (Figure 2(b)), an indicator of absorbing aerosol concentration, also showed higher value (0.77) over R1 compared to other regions. Furthermore, the trend of AI was similar to that of AOD, suggesting the long range transport of more absorbing aerosols from adjacent deserts in Mongolia and China over the January–May period (Figure 4). The AI had a consistently high value from March to June in all regions for every year, except in 2009. R2 showed high

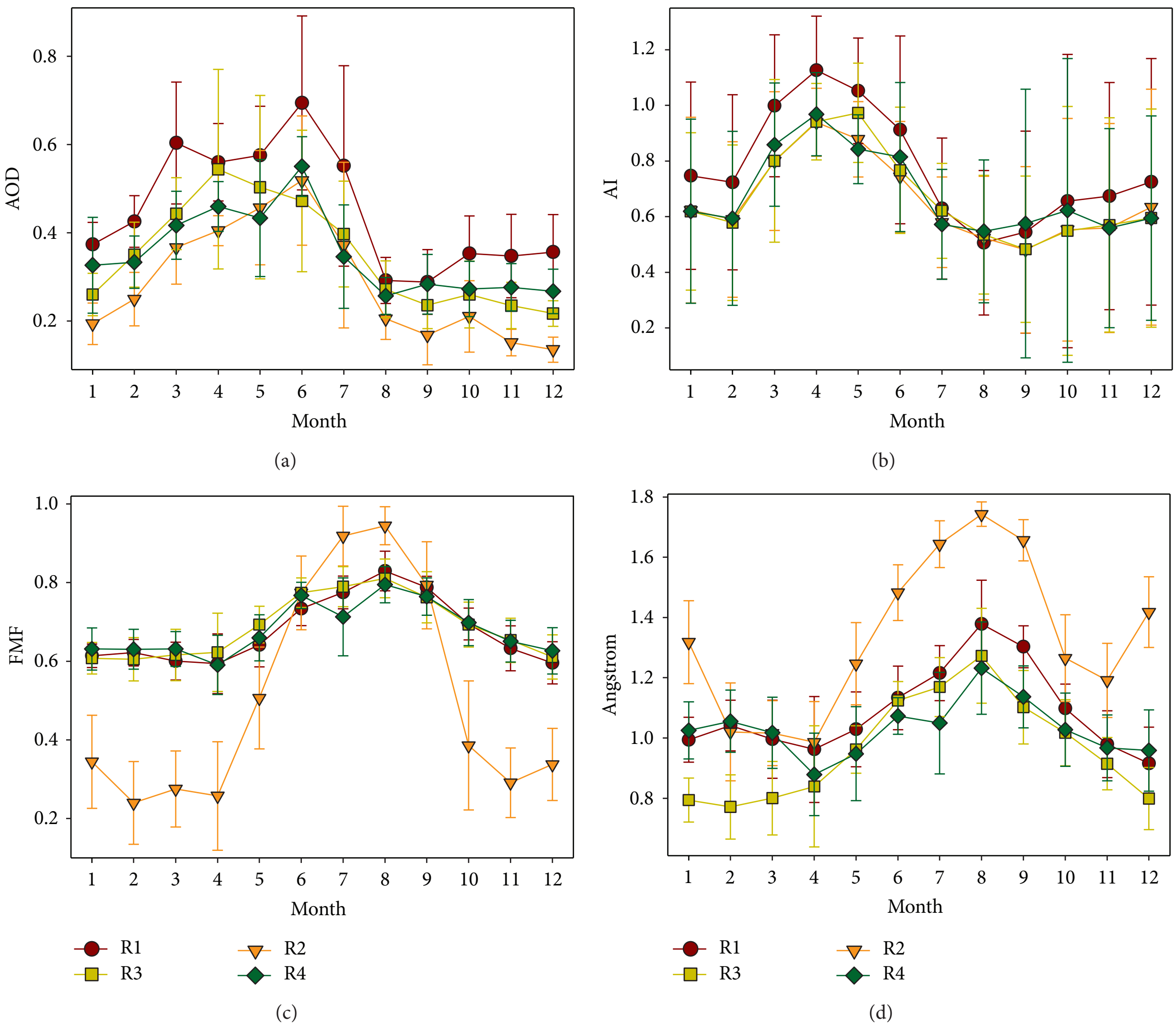

Figure 2: Monthly variability of (a) AOD, (b) AI (c) FMF and (d) Angstrom in R1 (red circle), R2 (orange inverted triangle), R3 (yellow square), and R4 (green diamond).

fluctuations in FMF variations compared to other regions (Figure 2(c)). In summer, FMF values were found to be high over R2 compared with oceanic area and it could be because of transported air pollutants from urban areas and strong convection current. In other seasons, FMF showed relatively low value over R2 compared with ocean and it could be due to stable condition of atmosphere. It was conjectured that R2 indicated the characteristics of inland area. All oceanic areas showed a higher average value of FMF compared to Korean inland (except during summer season). This indicates an abundance of sea salt accumulation mode aerosols over oceans, which have the highest probability of acting as CCN [22]. FMF values were found to be high during summer for all regions in all the years. The climatological mean of ANG, which indicates the size distribution of aerosols, is shown in Figure 2(d). ANG is found to be lower during spring season over all the regions (except over R2). Lower values of angstrom exponent indicate the dominance of larger coarse mode particles. Reference [20] has shown that there is a significant reduction in ANG over Korean region in past decade. Hence lower Angstrom exponent over all three regions affirms the influx of transported coarse mode dust aerosols from adjacent arid regions of Mongolia and China. The reason for higher AOD over R1 region compared to R2, in spite of having similar sources of transport, could be associated with the abundance of sea salt aerosols over R1 region, which further grows due to its hygroscopic nature [23]. Along with this, the significant reduction in aerosol concentration in past decade due to controlled anthropogenic activities over Korean inland [20] could be another reason for lower AOD over R2.

The average CIR was also higher (25.9 μm) over the R1 region (Figure 3(a)), compared to all other regions, indicating strong ice nucleation. This CIR enhancement could be associated with increase in transported dust particles from arid regions, which are reported as ideal cloud ice nuclei [11, 24, 25]. High concentrations of dust particles acting as ice nuclei in clouds could lead to changes in a cloud's microphysical

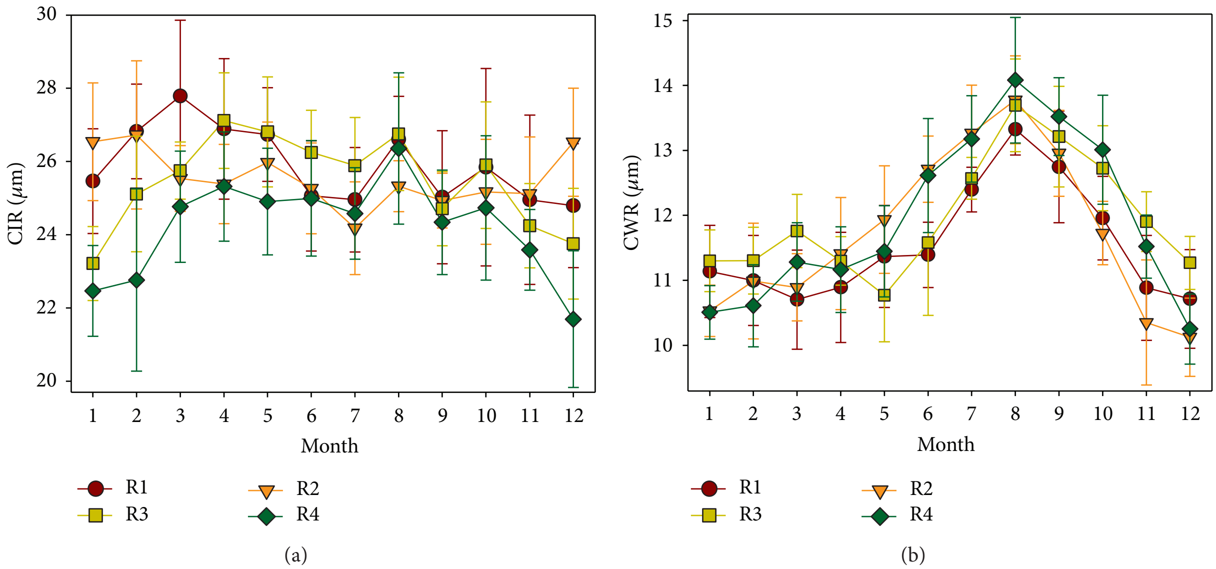

Figure 3: Same as Figure 2 but for (a) CIR and (b) CWR.

and radiative properties. Dust sources are mostly the deserts, dry lake beds, and agricultural areas with soil disturbance. Analogous to the FMF, the CWR consistently had higher values during the summer months for all years (Figure 3(b)). This could be associated with the changes in wind patterns during the Changma period (summer monsoon), bringing sea salt aerosol CCN to land and hence increasing the CWR (Figure 4(b)). R2 showed high fluctuations in FMF variations compared to other regions. It had a value of almost one during summer. It is assumed that there were transport of air pollutants and strong convection current over R2 region. The similarity in FMF and CWR trends indicates larger cloud water droplet nucleation due to sea salt fractions [26, 27]. On the other hand, FMF and CWR showed lower values during winter (December–February) (Figures 2 and 3), characterized with higher atmospheric stability as compared with summer. Additionally, cloud water nuclei were more dominant in winter than ice nuclei.

A climatological mean back trajectory image for different selected regions in different seasons is shown in Figures 4(a)–4(d). The simulations of HYSPLIT have shown that the long range transports of dust aerosols from continent of China are the major responsible component for this aerosol enhancement. The main path of air mass with aerosols transported over a long-range begins from the Taklamakan Desert through the Gobi Desert and Shandong Peninsula, and ends in the central region of the Korean peninsula (except during summer).

3.2. Aerosol Indirect Effect Estimates. The AIE which is the principal source of uncertainties in climate predictions [28] has been estimated for both CIP (Figure 5(a)) and CWP bins (Figure 5(b)) for each season from 2000 to 2009 as explained in Section 2. The climatological mean AIE values during 2000–2009 for fixed CIP and CWP bins in different seasons are shown in Figure 5. The AIE of ice droplets during different seasons showed Twomey (positive indirect effect) and anti-Twomey (negative indirect effect) effects (Figure 5(a)). R1 in spring showed a climatologically dominant Twomey effect and had a positive value of 0.09. This is related to an increase in aerosol particles from dry areas, forming clouds with more droplets and less precipitation efficiency, which in turn leads to high reflection of solar radiation. Oceanic regions in summer also showed dominant Twomey effect. It may be associated with an increase in the cloud amount. R2 showed a dominant anti-Twomey effect in summer and was found to have an average negative indirect effect value of −0.04. This could be related to the growth of cloud droplets and increased precipitation during the Changma period (summer monsoon). All regions except R2 showed an anti-Twomey effect in autumn. The AIE of cloud water droplets in each season generally had a negative value and showed an anti-Twomey effect (Figure 5(b)). This could be associated with an increase in water droplet nucleation, which would result from the high transport of sea salt aerosols from the oceans, subsequently working as efficient CCN. Sea salt can act as giant CCN (GCCN) which trigger early onset of precipitation [26]. R1 in spring showed a Twomey effect and had a positive AIE value of 0.02. This is related to an increase in aerosol particles transported from dry areas, resulting in high reflection and increased cloud lifetime.

Especially in Changma (summer monsoon in June-July) period, there persists strong moist environment. Hence aerosol indirect effect could be different as compared to dry period. Cloud in this Asian monsoon region also shows different structures and components according to the cloud levels or height. Especially, cloud height and type are shown to be as important as cloud cover in modifying the radiation field of the earth-atmosphere system [16].

Hence the climatological mean AIE during Changma period is investigated during 2000 to 2009 by considering the cloud level height. The cloud levels have been divided into

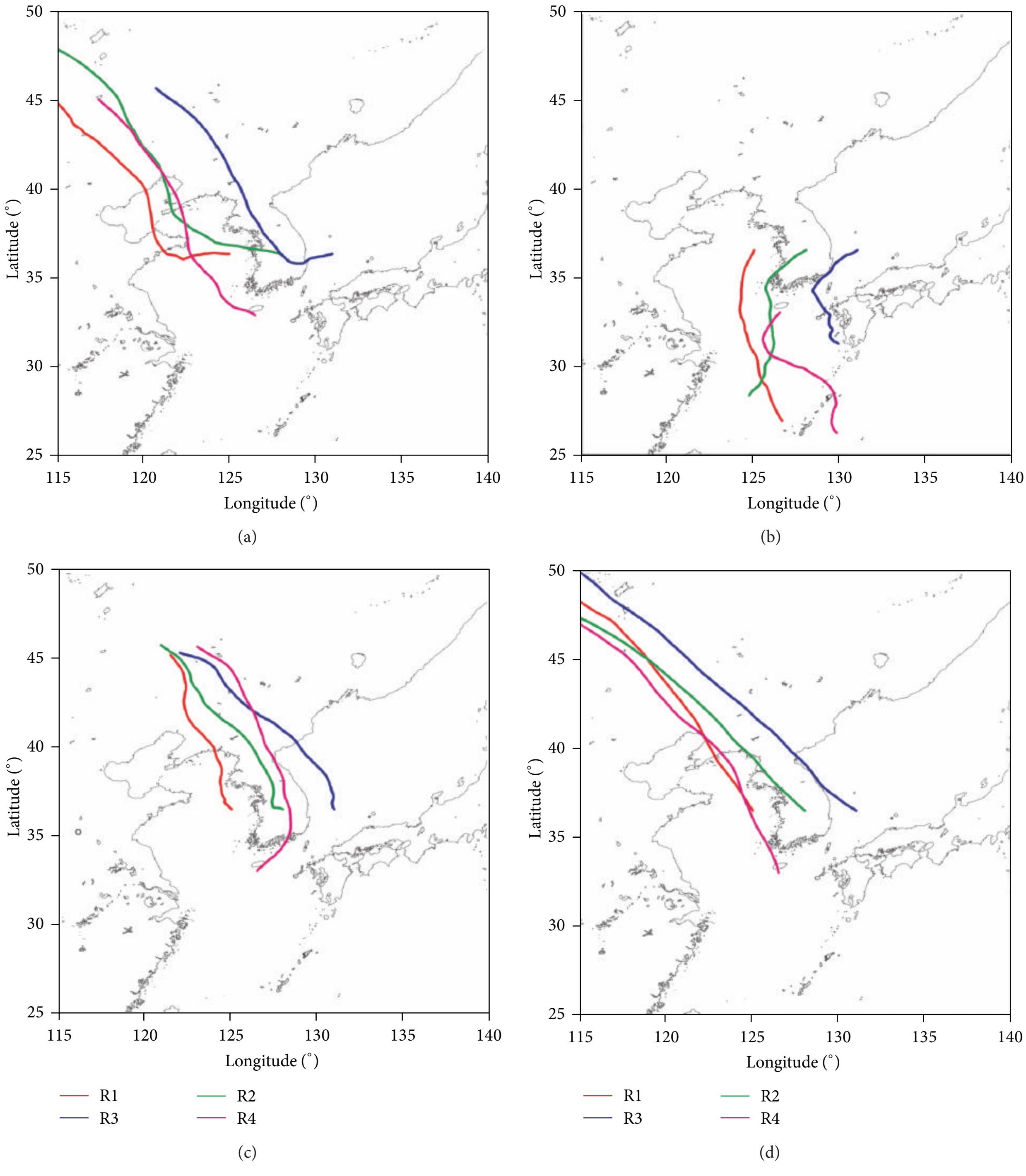

Figure 4: Climatological mean back-trajectories of the air mass arrived over R1 (red), R2 (green), R3 (blue), and R4 (pink) in (a) spring, (b) summer, (c) autumn, and (d) winter.

three intervals of cloud top pressure (high cloud, $Pc \geq 440$ mb; middle cloud, $440 \text{ mb} < Pc \leq 680$ mb; and low cloud, $Pc > 680$ mb) [29]. The AIE has been estimated for both CIP and CWP bins during Changma period in each region for all three types of cloud during 2000 to 2009 and hence climatological mean value is computed (Figure 6). Since low clouds do not contain ice droplets, AIE for ice droplets has been estimated only for high and middle clouds (Figure 6(a)). The AIE for ice droplets in each cloud level also showed a dominant anti-Twomey effect (negative indirect effect), indicating the increase in cloud drop size with enhanced aerosols. Middle clouds also showed a strong anti-Twomey effect (except over R3). However, high cloud in R1 showed a Twomey effect and had a positive value of 0.01. This could be associated

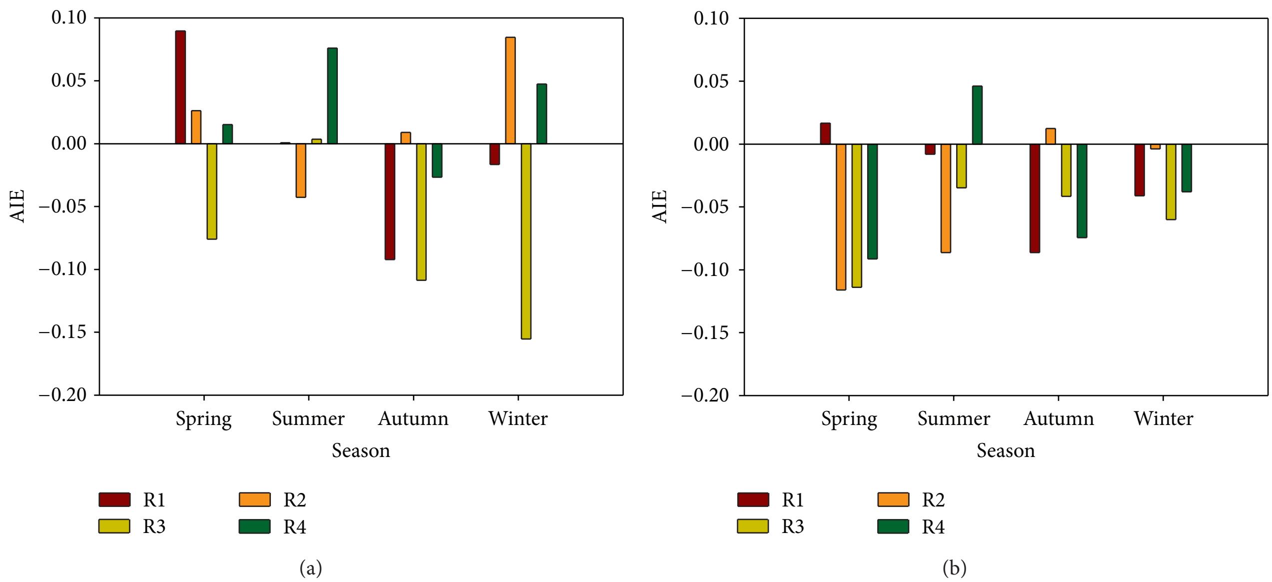

Figure 5: Seasonal climatological mean of aerosol indirect effect of (a) ice and (b) water particle in R1 (red), R2 (orange), R3 (yellow), and R4 (green).

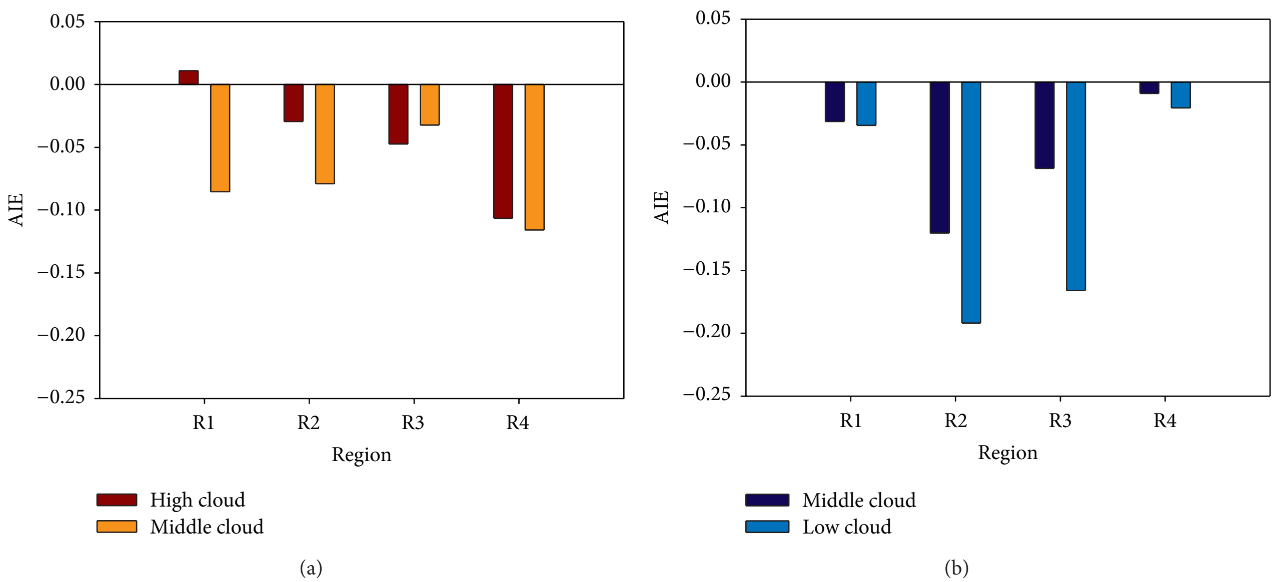

Figure 6: Regional climatological mean aerosol indirect effect during Changma period for (a) ice in high (red) and middle cloud (orange) and (b) water particle in middle (blue) and low cloud (sky blue).

with high reflection at the cloud top. The AIE for CWP bins has been estimated for middle and low clouds, since high cloud has fewer amounts of water drops compared to ice pellets (Figure 6(b)). In particular, low clouds in each region showed a strong anti-Twomey effect and it could be associated with the development of precipitation in comparison with middle cloud. The enhanced anti-Twomey effect could be attributed to enhanced moisture content available to individual hygroscopic aerosols, increasing cloud drop growth, resulting in precipitation. The R2 region showed a strong anti-Twomey effect in middle (−0.12) and low clouds (−0.19). This clearly indicates that the development of precipitation during Changma is influenced by an anti-Twomey effect over Korean inland. The differences in AIE during entire summer and exclusively during Changma period could be due to the fact that Korean summer consists of dry clear sky periods and wet Changma periods. The AIE for ice droplets (for fixed CIP bins) during Changma period also showed a dominant anti-Twomey effect. In particular, the AIE value at low clouds showed a strong anti-Twomey effect, indicating higher probability of precipitation development compared to middle clouds. Finally, the AIE during the Changma period could be considered as a clear indicator for precipitation predictions.

Several studies report AIE estimates over different parts of the world. The AIE values reported in this study are in agreement with those reported in earlier studies. It reported indirect effect values of 0.07 to 0.11 on different experimental days using ground based method over Oklahoma [17]. It also obtained similar AIE values using ground based observations [30]. AIE value is reported between 0.13 and 0.19 in Alaska region [31]. It also found AIE values of 0.03 to 0.71 over East China Sea region [2]. Even though positive AIE values have been majorly reported, few studies report negative indirect values in certain environmental conditions [6, 24]. AIE was studied on two contrasting monsoon seasons over Indian region [10]. It is found that the AIE values were positive during bad monsoon years and were negative during good monsoon years. The negative indirect values ranged between −0.007 and −0.22 over different regions in good monsoon conditions, indicating the increase in cloud effective radii with changes in aerosol loading and hence inducing precipitation. However the positive indirect effect values were found to be ranging between 0.15 to 0.37 in bad monsoon condition, which reduces the cloud effective radii and precipitation.

4. Summary and Conclusions

This study presents the seasonal variability of aerosols and cloud properties by using Terra MODIS satellite data for four different regions in Korean peninsula over 10 years. The selected regions include Yellow sea (R1, 124°–126°E & 35°–38°N), Korean inland (R2, 127°-129°E & 35°-38°N), East sea (R3, 130°–132°E & 35°–38°N), and South sea (R4, 125°–128°E & 32°–34°N). It is found that aerosol parameters show significant seasonal and monthly variability, which in turn influences cloud properties.

The AOD and AI values were found to be higher during January to June for all years. This obviously is associated with the long range transport of aerosols from deserts and continent of China, indicated by small Angstrom exponent values, representing the presence of large dust aerosols. The CIR also showed higher values during spring, while the CWR and FMF showed an increase during summer in all years. This is related to an abundance of accumulation mode aerosols which influence condensation, formation, and enhancement of cloud droplet size. The AOD, CIR, and AI were found to be higher in R1 than other regions. The FMF over R2 is higher in summer as compared with other seasons.

The AIE values for ice droplets in each year were estimated for different seasons and found to have both positive and negative indirect effects. However, the AIE of cloud water droplets in each season generally had a negative value. The AIE during the Changma period at different cloud levels showed a strong anti-Twomey effect, especially in low cloud for water droplets. This portrays that aerosols play an important role in increasing cloud drop size and hence precipitation during Changma period.

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References

[1] A. S. Ackerman, O. B. Toon, D. E. Stevens, A. J. Heymsfield, V. Ramanathan, and E. J. Welton, "Reduction of tropical cloudiness by soot," *Science*, vol. 288, no. 5468, pp. 1042–1047, 2000.

[2] G. Pandithurai, T. Takamura, J. Yamaguchi et al., "Aerosol effect on cloud droplet size as monitored from surface-based remote sensing over East China Sea region," *Geophysical Research Letters*, vol. 36, no. 13, Article ID L13805, 2009.

[3] M. G. Manoj, P. C. S. Devara, S. Joseph, and A. K. Sahai, "Aerosol indirect effect during the aberrant Indian Summer Monsoon breaks of 2009," *Atmospheric Environment*, vol. 60, no. 1, pp. 153–163, 2012.

[4] S. Twomey, "The influence of pollution on the shortwave albedo of clouds," *Journal of Atmospheric Sciences*, vol. 34, no. 7, pp. 1149–1152, 1977.

[5] B. A. Albrecht, "Aerosols, cloud microphysics, and fractional cloudiness," *Science*, vol. 245, no. 4923, pp. 1227–1230, 1989.

[6] T. Yuan, Z. Li, R. Zhang, and J. Fan, "Increase of cloud droplet size with aerosol optical depth: an observation and modeling study," *Journal of Geophysical Research D*, vol. 113, no. 4, Article ID D04201, 2008.

[7] P. K. Patra, S. K. Behera, J. R. Herman, S. Maksyutov, H. Akimoto, and T. Yamagata, "The Indian summer monsoon rainfall: interplay of coupled dynamics, radiation and cloud microphysics," *Atmospheric Chemistry and Physics*, vol. 5, no. 8, pp. 2181–2188, 2005.

[8] V. R. Kiran, M. Rajeevan, S. V. B. Rao, and N. P. Rao, "Analysis of variations of cloud and aerosol properties associated with active and break spells of Indian summer monsoon using MODIS data," *Geophysical Research Letters*, vol. 36, no. 9, Article ID L09706, 2009.

[9] R. L. Bhawar and P. C. S. Devara, "Study of successive contrasting monsoons (2001-2002) in terms of aerosol variability over a tropical statio Pune, India," *Atmospheric Chemistry and Physics*, vol. 10, no. 1, pp. 29–37, 2010.

[10] A. S. Panicker, G. Pandithurai, and S. Dipu, "Aerosol indirect effect during successive contrasting monsoon seasons over Indian subcontinent using MODIS data," *Atmospheric Environment*, vol. 44, no. 15, pp. 1937–1943, 2010.

[11] P. Chylek, M. K. Dubey, U. Lohmann et al., "Aerosol indirect effect over the Indian Ocean," *Geophysical Research Letters*, vol. 33, no. 6, Article ID L06806, 2006.

[12] A. K. Srivastava, S. Tiwari, P. C. S. Devara et al., "Pre-monsoon aerosol characteristics over the Indo-Gangetic Basin: implications to climatic impact," *Annales Geophysicae*, vol. 29, no. 5, pp. 789–804, 2011.

[13] J.-H. Jeong, D.-I. Lee, C.-C. Wang, S.-M. Jang, C.-H. You, and M. Jang, "Environment and morphology of mesoscale convective systems associated with the Changma front during 9-10 July 2007," *Annales Geophysicae*, vol. 30, no. 8, pp. 1235–1248, 2012.

[14] A. Jayaraman, "Aerosol radiation cloud interactions over the tropical Indian Ocean prior to the onset of the summer monsoon," *Current Science*, vol. 81, no. 11, pp. 1437–1445, 2001.

[15] E.-K. Seo, "Characteristics of summer rainfall over East Asia as observed by TRMM PR," *Journal of Korean Earth Science Society*, vol. 32, no. 1, pp. 33–45, 2011.

[16] T. Chen, W. B. Rossow, and Y. Zhang, "Radiative effects of cloud-type variations," *Journal of Climate*, vol. 13, no. 1, pp. 264–286, 2000.

[17] G. Feingold, W. L. Eberhard, D. E. Veron, and M. Previdi, "First measurements of the Twomey indirect effect using ground-based remote sensors," *Geophysical Research Letters*, vol. 30, no. 6, p. 1287, 2003.

[18] A. K. Srivastava, K. Ram, P. Pant, P. Hegde, and H. Joshi, "Black carbon aerosols over Manora Peak in the Indian Himalayan foothills: implications for climate forcing," *Environmental Research Letters*, vol. 7, no. 1, Article ID 014002, 2012.

[19] K. O. Ogunjobi, Y. J. Kim, and Z. He, "Aerosol optical properties during Asian dust storm episodes in South Korea," *Theoretical and Applied Climatology*, vol. 76, no. 1-2, pp. 65–75, 2003.

[20] A.-S. Panicker, D.-I. Lee, Y.-V. Kumkar, D. Kim, M. Maki, and H. Uyeda, "Decadal climatological trends of aerosol optical parameters over three different environments in South Korea," *International Journal of Climatology*, vol. 33, no. 8, pp. 1909–1916, 2012.

[21] S.-H. Park, A. S. Panicker, D.-I. Lee et al., "Characterization of chemical properties of atmospheric aerosols over anmyeon (South Korea), a super site under global atmosphere watch," *Journal of Atmospheric Chemistry*, vol. 67, no. 2-3, pp. 71–86, 2010.

[22] G. C. Roberts, M. O. Andreae, J. Zhou, and P. Artaxo, "Cloud condensation nuclei in the Amazon Basin: "Marine" conditions over a continent?" *Geophysical Research Letters*, vol. 28, no. 14, pp. 2807–2810, 2001.

[23] C. A. Randles, L. M. Russell, and V. Ramaswamy, "Hygroscopic and optical properties of organic sea salt aerosol and consequences for climate forcing," *Geophysical Research Letters*, vol. 31, no. 16, Article ID L16108, 2004.

[24] G. Myhre, F. Stordal, M. Johnsrud et al., "Aerosol-cloud interaction inferred from MODIS satellite data and global aerosol models," *Atmospheric Chemistry and Physics*, vol. 7, no. 12, pp. 3081–3101, 2007.

[25] S. Dipu, T. V. Prabha, G. Pandithurai et al., "Impact of elevated aerosol layer on the cloud macrophysical properties prior to monsoon onset," *Atmospheric Environment*, vol. 70, no. 1, pp. 454–467, 2013.

[26] M. Konwar, R. S. Maheskumar, J. R. Kulkarni, E. Freud, B. N. Goswami, and D. Rosenfeld, "Aerosol control on depth of warm rain in convective clouds," *Journal of Geophysical Research*, vol. 117, no. 13, Article ID D13204, 2012.

[27] J. R. Kulkarni, R. S. Maheskumar, S. B. Morwal et al., "The Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX): overview and preliminary results," *Current Science*, vol. 102, no. 3, pp. 413–425, 2012.

[28] Intergovernmental Panel on Climate Change (IPCC), S. Solomon, D. Qin et al., *Climate Change 2007, The Physical Science Basis*, Cambridge University Press, New York, NY, USA, 2007.

[29] W. B. Rossow and R. A. Schiffer, "Advances in understanding clouds from ISCCP," *Bulletin of the American Meteorological Society*, vol. 80, no. 11, pp. 2261–2287, 1999.

[30] B.-G. Kim, S. E. Schwartz, M. A. Miller, and Q. Min, "Effective radius of cloud droplets by ground-based remote sensing: relationship to aerosol," *Journal of Geophysical Research D*, vol. 108, no. 23, p. 4740, 2003.

[31] T. J. Garrett, C. Zhao, X. Dong, G. G. Mace, and P. V. Hobbs, "Effects of varying aerosol regimes on low-level Arctic stratus," *Geophysical Research Letters*, vol. 31, no. 17, Article ID L17105, 2004.